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A new measurement of the ^{2}H(p,γ)^{3}He cross section at the BBN energies

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Summary. — The Big Bang Nucleosynthesis (BBN) models describe the production of light nuclei in the first minutes of cosmic time. When, as a consequence of temperature decrease of the Universe, the equilibrium between deuteron production through p(n, γ)^{2}H and its photo-dissociation was broken, the deuterium nuclei just created were destroyed through the ^{2}H(^{2}H,p)^{3}H, the ^{2}H(^{2}H,n)^{3}He and the ^{2}H(p,γ)^{3}He reactions. The overall primordial deuterium abundance is thus determined by the cross sections of all these reactions, experimentally studied in nuclear laboratories since the middle of last century. Recently, precise measurements of the primordial deuterium abundance have opened the possibility to precisely constrain the primordial baryon-to-photon ratio, independently from evaluations based on the Cosmic Microwave Background (CMB) measurements. For their interpretation, the deuterium abundance data require equally precise nuclear physics data: the main obstacle to an accurate theoretical ^{2}H abundance evaluation is the poor knowledge of the ^{2}H(p,γ)^{3}He cross section at the relevant energies. The aim of the present work is to describe the experimental effort undertaken by the LUNA collaboration, aimed to measure with unprecedented precision the reaction cross section in the BBN energy range (30<Ec.m.[keV]<300).

1. – Introduction

Deuterium is the first nucleus produced in the Universe and its primordial abundance is very sensitive to cosmological parameters like the baryon density and the number of the neutrino families [1-3]. In the standard BBN the only free parameter is the baryon density, usually normalised to the black-body photon density $\eta = n_B/n_\gamma$: these two quantities change with time and temperature but their ratio stays constant from the end of BBN to the present epoch. Since standard BBN is a one-parameter theory, the comparison of any abundance measurement with the BBN calculation determines η the baryon-to-photon ratio, or equivalently the present baryon density $\Omega_{b,0}$(Fig.1-*left*) [4].

(*) On behalf of the LUNA Collaboration.

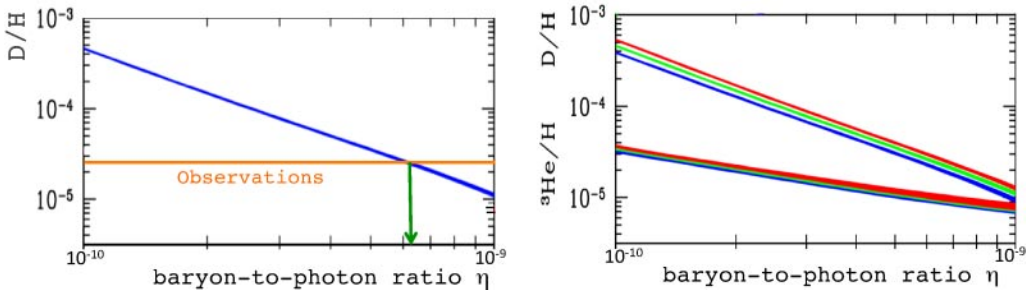

Fig. 1. – *Left* – BBN predictions for the D/H ratio as a function of η (in blue color) are compared with observations (in orange) [1, 3]: the crossing of the two curves settles η; *Right* – The D/H and ^{3}He/H ratio for different N_{eff} values [1] (blue =2, green =3, red =4).

New observations and analysis of quasar absorption systems at high redshift have significantly improved our knowledge of D/H. In updated work presented in 2018 a notable precision of 1.6% on this quantity has been achieved: $10^5(D/H)_P = (2.527 \pm 0.030)$ [3].

The BBN predictions for the D/H ratio are influenced by the cross sections of several nuclear reactions [2], whereas the ^{2}H(p,γ)^{3}He reaction represents the main source of uncertainty because only one data set exists at the BBN energies [5] and with a large error (9%). Theoretical calculations [6], based on an ab-initio approaches, predict significantly higher values for the cross section, at the level of 20%. If the BBN codes adopt these last theoretical values (provided with no error), the comparison with observational D/H abundance, constrains the $\Omega_{b,0}$ quantity to $100\Omega_{b,0}h^2(BBN)$= $(2.166 \pm 0.015 \pm 0.011)$ [3]. The analysis of the CMB anisotropies, recently measured by Planck, yields conversely to $100\Omega_{b,0}h^2(CMB)$= (2.226 ± 0.023) [3]. The two determinations are broadly consistent but their difference corresponds to a $\sim 1.5\ \sigma$ discrepancy, which is mitigated if the empirically measured ^{2}H(p,γ)^{3}He cross section is used as input for the BBN calculations.

A new measurement with a 3% accuracy is therefore crucial to push down the BBN uncertainty on deuterium abundance to the same level of observations and to eventually constrain the number of relativistic degrees of freedom N_{eff} (see Fig.1-right).

2. – The LUNA measurement

At the energies of interest the ^{2}H(p,γ)^{3}He reaction proceeds through a not resonant mechanism directly to the ground state of ^{3}He. The incoming proton can be captured both in a *s*-wave or *p*-wave orbital angular momentum state and the emitted gamma-ray shows a not isotropic angular distribution dominated by the M1 and E1 components. The low energy limit of this reaction cross section is well known thanks to the LUNA measurement performed in 2002 under the solar Gamow peak [8] and shown in Fig.2-*left*. At solar energies (Ec.m. < 50 keV), the reaction was studied also by Griffiths et al. [9], Schmid et al. [10] and Bystritsky et al. [11]. Some discrepancies exist among these data sets at the lower energies: according to [10] they are likely due to the wrong stopping power adopted for the heavy-ice target in the Griffiths's and Bailey's works and affecting the S-factor value by about 15%. At higher energies, in the 200 keV < Ec.m. <1 MeV energy range, the ^{2}H(p,γ)^{3}He cross section has been studied by Griffiths et al. [12]

and Bailey et al. [13] again with a solid heavy ice target. In the same energy range Warren et al. [14] has conversely measured the cross section of ^{3}He photodisintegration process with a gas target: the deduced astrophysical factor for the inverse reaction is in a good agreement with direct measurement data. Finally in energy range between 70 and 170 keV only the measurement by Ma et al. is currently available (see Fig.2-*left*) with a systematical error of 9% [5]. Several authors have performed interpolations of the existing data: Adelberger et al. in [16] has fitted the S-factor data from [13], [8], [10] and [5] with a second order polynomial: the blue band in Fig.2-*left* represents the 68% lower and upper bounds of his best-fit results. Angulo et al. performed a fit for the NACRE compilation [17] and an updated version of this fit was developed by [18], adding the post-NACRE data set of LUNA [8], extending thus the energy range down to 2 keV. A further evaluation of the ^{2}H(p,γ)^{3}He S-factor is due to Descouvemont et al. in [19]. In Fig.2-*left* the results of all these works are quoted together with the new theoretical ab-initio calculations from [6] .

The Q-value of the ^{2}H(p,γ)^{3}He reaction is quite large (Q=5.493 MeV) so that the gamma-ray energy is above the natural radioactivity endpoint, a feature that fully exploits the cosmic ray suppression at the Gran Sasso National laboratory. The 400 kV electrostatic LUNA accelerator is able to provide intense current of protons up to 500 μA : the beam power is measured through a constant temperature gradient calorimeter precisely calibrated by comparison with a Faraday cup measurement taken in vacuum conditions. In order to achieve the needed high precision the ^{2}H(p,γ)^{3}He cross section measurements have been repeated by exploiting two different experimental approaches.

In the first one, the γ rays emitted by the reaction were detected by a cylindrical BGO detector having a length of 28 cm with a radial thickness of 7 cm. The adopted crystal is optically divided into six sectors, each covering an azimuthal angle of 60 degrees and the chamber and the calorimeter were hosted inside the BGO hole. With this set-up, the counting rate (full detection γ-peak) was of the order of 10^4 - 10^5 events/hour in the energy range of interested, making the measurement with the BGO detector relatively fast for reaching 10000 events under the photopeak to ensure a low statistic uncertainty (<1%). The almost 4π geometry reduced the dependence of the counting rate on the angular distribution of the emitted γ rays and the high detection efficiency for 5.5 MeV-γ's (62%) made this setup particularly suited to extend the measure at the lowest beam energies (E_{cm}=30-200 keV). The second phase was based on a HpGe detector, placed at a distance of $\sim$4 cm from the beam axis and coupled to a a windowless deuterium gas target, 33 cm long. Thanks to high energy resolution of the HpGe (10 keV at 6 MeV) this configuration is less sensible to beam induced backgrounds at the higher energies (E_{cm} > 140 keV). The explored energy window (E_{cm}=70-270 keV) was chosen in order to guarantee a sizeable overlap with the BGO-based measurements. As an interesting feature, this setup offers also the possibility to measure the angular distribution of the emitted gammas because of the Doppler effect: from the measured energy shape of the full absorption peak, the γ angular distribution can be deduced and the predictions nuclear physics models validated (see Fig.2-*right*). The data shown in Fig.2-*right* clearly disfavour an isotropic gamma distribution.

In both approaches, several checks have been performed to reduce possible systematical effects. The beam induced background has been precisely evaluated by repeating each measurement with the target filled by inert gas (He). The efficiency have been determined with a precision of $\sim$3% thanks to the experimental data taken with radioactive sources (^{137}Cs, ^{60}Co and ^{88}Y) at low energies and with the well-known resonant reaction ^{14}N(p, γ)^{15}O at E_r = 259 keV, emitting γ rays in the p+d energy range.

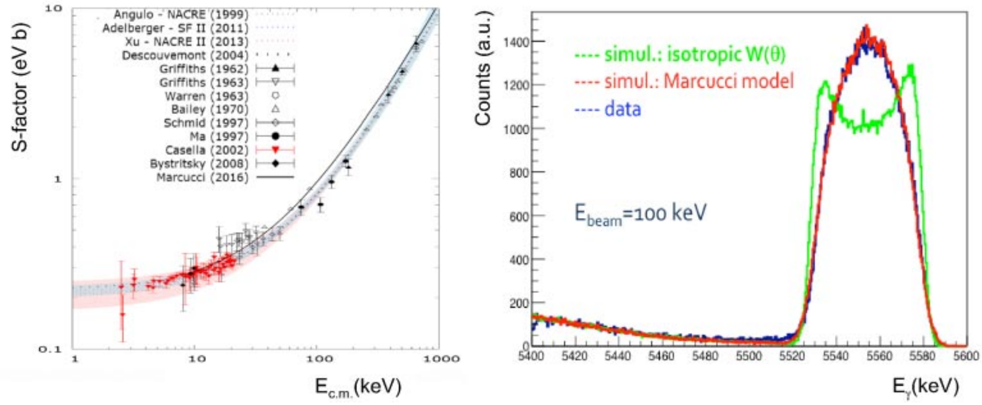

Fig. 2. – *Left* – Literature data for the ^{2}H(p,γ)^{3}He reaction, together with the different existing interpolations and the new theoretical models predictions (see text for details); *Right* – The measured shape of the full γ absorption peak (in blue color) is compared with expectations from the theoretical ab-initio models [6] (red) and by an isotropic γ emission (green)

In general, a smooth cross section variation with the energy has been observed, with values on average higher respect to the literature data and the Adelberger interpolation. A complete and high precision set of data points has now been acquired and the data analysis is in progress.

These new precision measurements are offering the possibility to fully exploit the D/H primordial abundance as a probe of ΛCDM and to provide important experimental grounds for theoretical nuclear physics.

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